The Problem of Foams

James A. Glazier (Indiana), Peter Cloetens (ESRF), Reynaud Delannay (Rennes), Francois Graner (Grenoble), Isabelle Cantat (Rennes), Jerome Lambert (Rennes), Igor Veretennikov (Notre Dame)

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Why Are Foams Interesting?

Many Industrial Applications:

Fire-Fighting, Fractionation, Filtration, Flotation, Transport, Bomb Disposal, Beer, Foods, Cleaning, Metallic Foams, Solid Foams, Airplane De-icing

Prototypes for Other Materials:

Ceramic Sintering, Emulsions, Langmuir monolayers, Low anisotropy metallic annealing

The trick is to sell the customer a product which is mostly air.

Confectionary manufacturer

“The Physics of Foam”, p. 192

What is Foam?

2-Phase system:

dispersed/continuous

The Laws:

Laplace-Young:

$$\Delta p = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

Plateau:

$$\varphi = \cos^{-1}(-1/C)$$

2D: 120^{o}
3D: 109.5^{o}

3D MRI of gelatinous foam (43h)

128x128x256, 100µm

7T, 300MHz

Foams Have Unusual Mechanical Properties

Keys to Applications

Solid at low shear stress, liquid at high shear stress
Lightweight
Good at absorbing shocks
Interesting properties under compression

Usefulness as Prototypes

Macroscopic
Can relate bulk properties to individual local events
Relatively simple
Tunable

While the mechanical properties of foams clearly must result from the combination of the properties of their components (*e.g.* liquid viscosity and surface tension, gas compressibility, solid elastic properties) and their geometric structure.

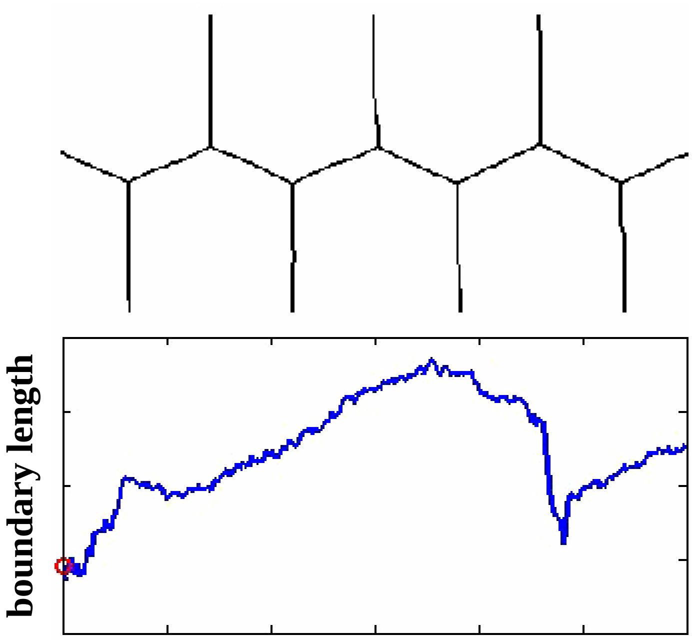
NO PREDICTIVE THEORY!!! (yet)

Some Properties

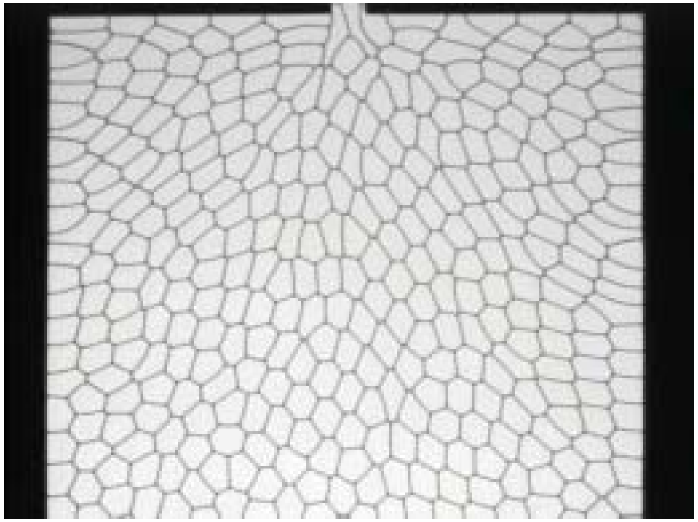
Solid/Liquid

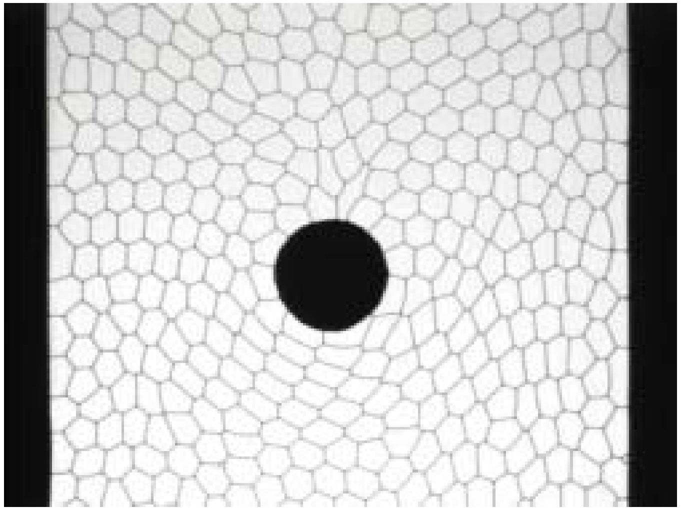
El. Mod ~ 10Pa

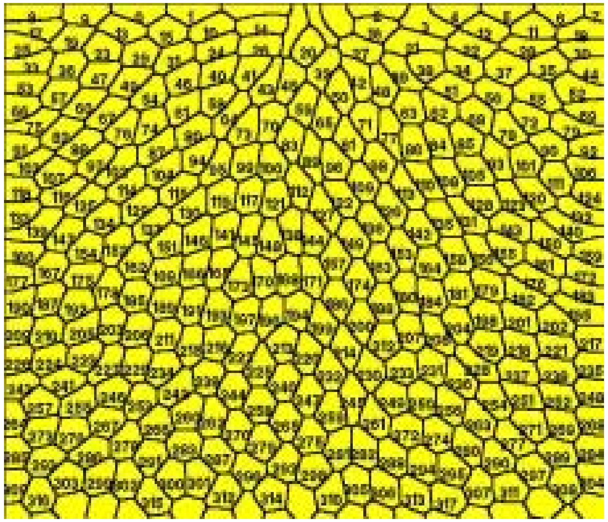
T1 Topological Event

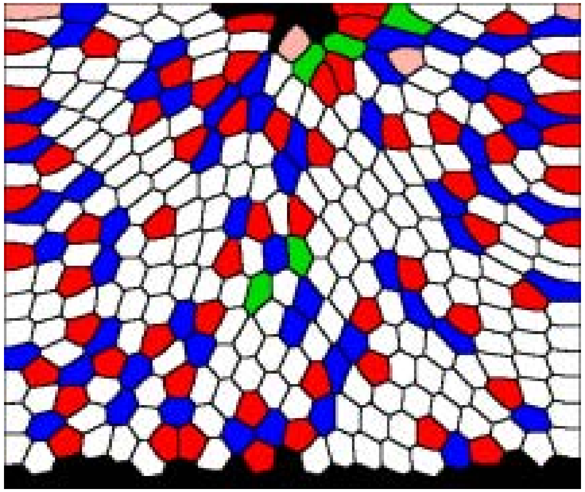


2D Experiment



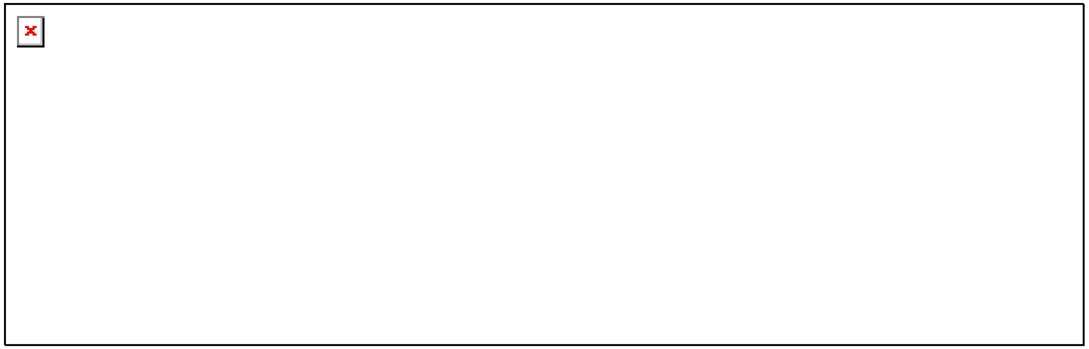




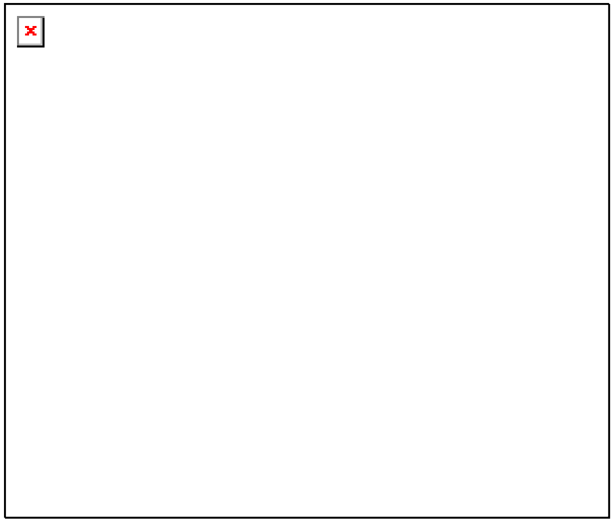


Hele-Shaw cell: width 100 mm, spacing 0.5 mm.
640x480, 2840 frames at 15fps

T1 Tensor



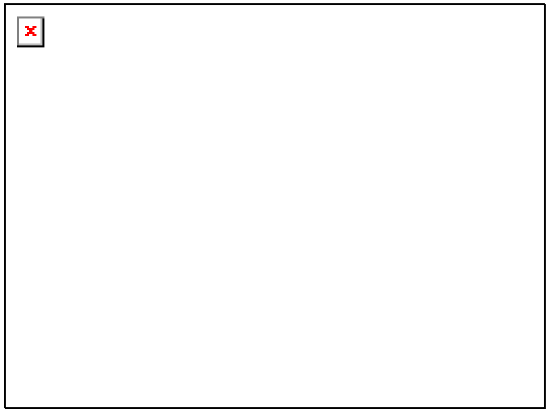
T1: Edge Created, Edge Destroyed

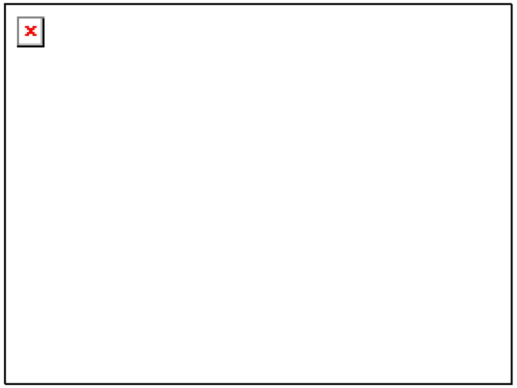


Creation
Destruction

Can be represented as an ellipse with major/minor axes same direction as eigenvectors and proportional to eigenvalues

Stress, Strain



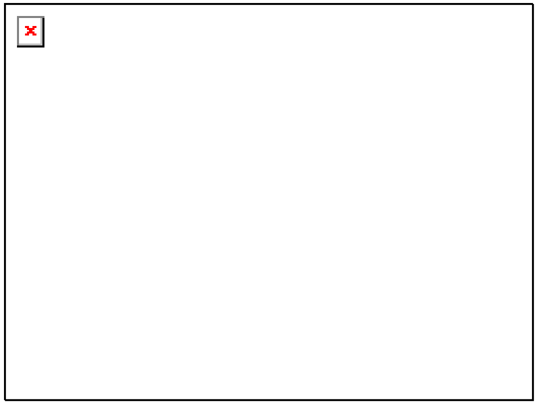


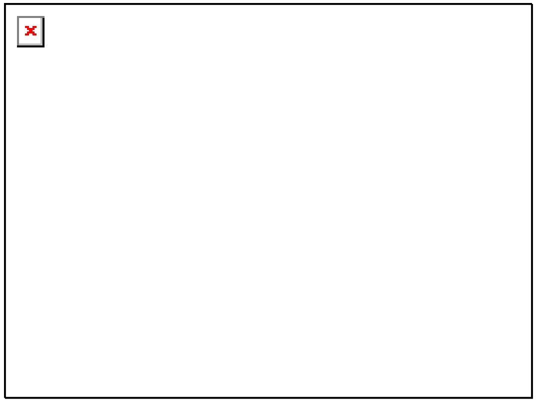
$$\sigma_{xx} - \sigma_{yy}$$

Positive

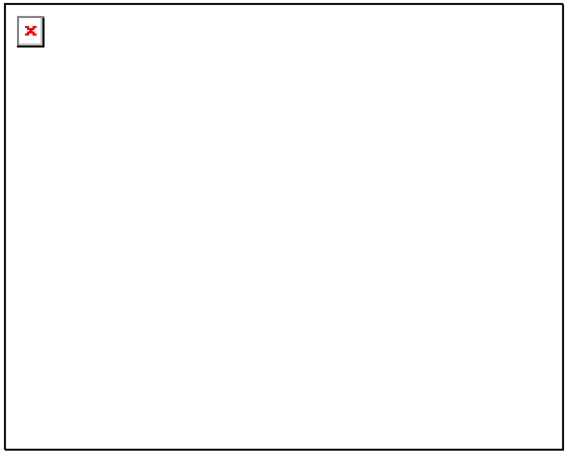
Zero, within e

Negative

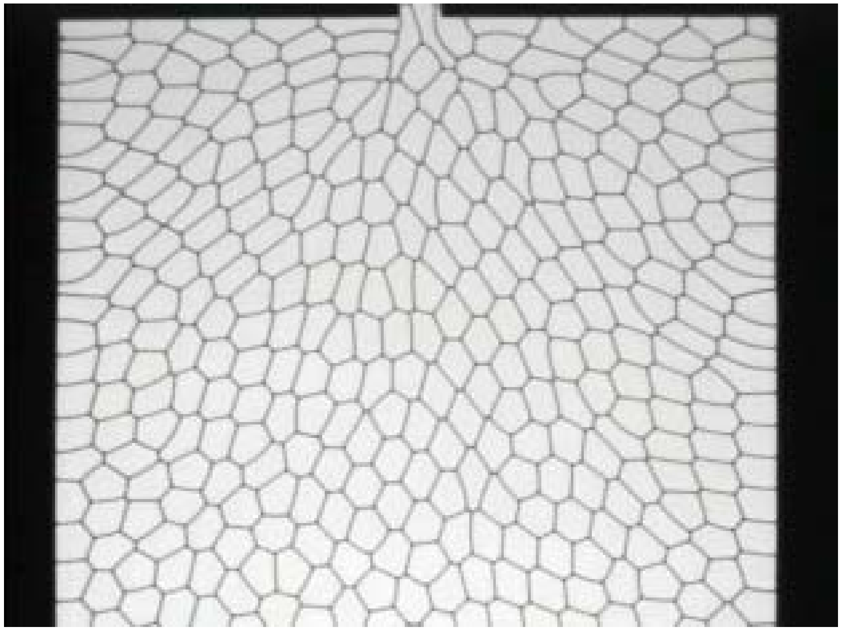




‘Young’s Modulus’

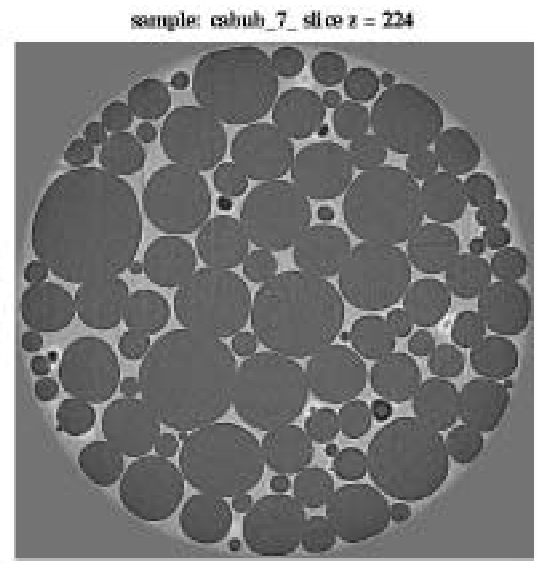


Wet vs. Dry Foams



Dry Foam: Polygonal Bubbles, Thin Walls

Wet Foam:Rounded Bubbles, Thick Borders and Walls



Key Quantifiers of Foams

Static:

- Mean Length Scale
- Bubble Size Distribution
- Bubble Topology Distribution
- Size-Size Correlations
- Size-Topology Correlations
- Distribution of Fluid

Key Questions about Foams

Dynamic:

•Evolution of Mean Length Scale

•How do individual bubbles grow and shrink?

•Do the Bubble Size Distribution and Bubble Topology Distribution reach a time invariant *scaling* state?

•How do Correlations evolve in time? Under stress?

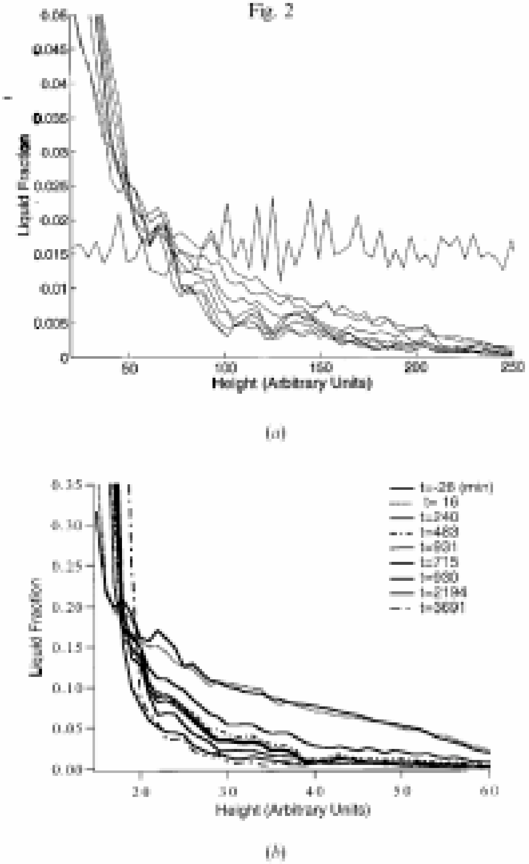
•Drainage and redistribution of fluid

•How do individual bubbles change shape?

•How do macroscopic properties depend on Quantifiers?

Drainage

Fig. 2



Liquid profiles for free drainage as a function of time: (*a*) Potts model simulation; (*b*) MRI experiment data.

The Growth Law Question

In 2-D dry foam the rate of growth of a bubble depends only on its number of sides!

Von-Neumann's Law: $\mathrm{d}a_n/\mathrm{dt} = \kappa\,(n\text{-}6)$

This law is exact in the dry foam limit.

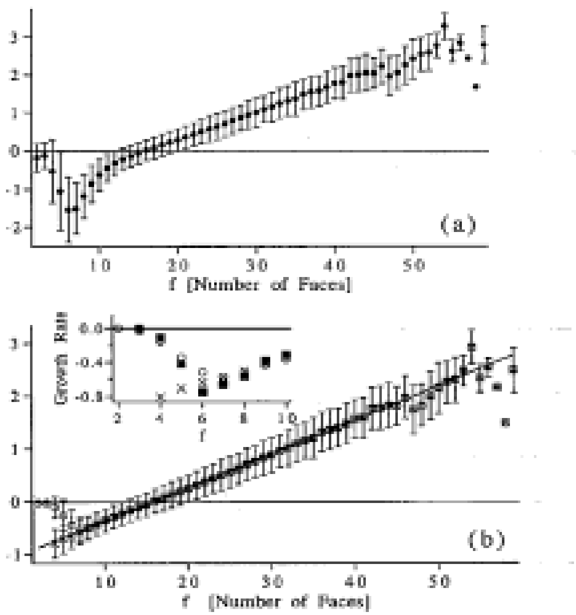
In 3-D we don't know if there is a similar result because the mathematics is different. Simulations suggest that for dry foams $\mathrm{d}v_f^{\,2/3}/\mathrm{dt} = \kappa\,\mathrm{g}(f\text{-}f_0)$, where g is nearly linear.

For wet foams in either 2-D or 3-D we have the Lifschitz-Slyozov Law: $\mathrm{d}v_f/\mathrm{dt} = \kappa\,(1/r\text{-}1/r_0)$

Experimental results are limited and ambiguous.

Growth Law Data

Simulation and Experiment



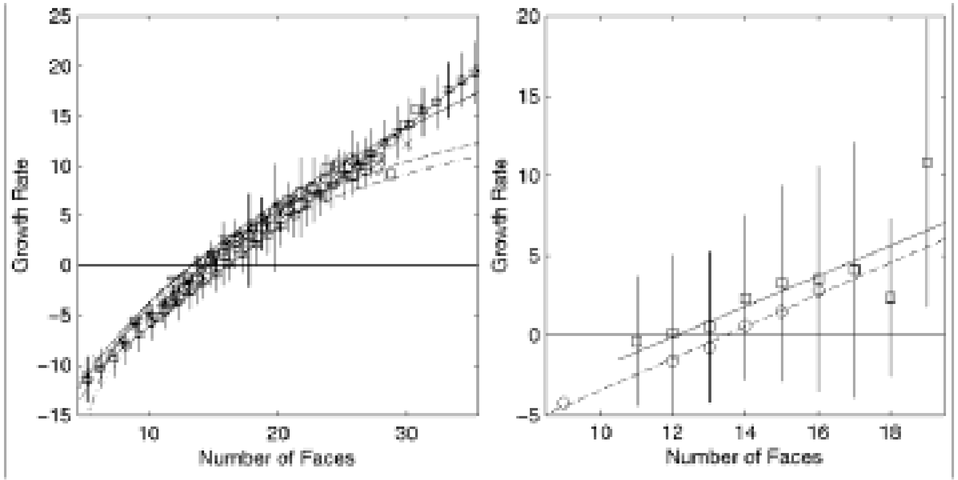


Figure 2a. Growth rates as a function of number of faces for Fortes' edge and vertex models (Dashed lines), Mullins' model (Solid Line), Kawasaki's vertex model (Squares, Circles and Diamonds), Weygand's vertex model (Dotted Line), Monnereau *et al.*'s boundary dynamics model (Triangles), Wakai's boundary dynamics model (Xs and Stars) and Glazier's Potts model (Star of David). 2b. Monnereau *et al.*'s optical tomography experiments (Circles) and our MRI experiments (Squares).

Problem

•Foams are White (*i.e.* they are hard to see through)

Possible Solutions:

•Two-dimensional Experiments: Fast, Good Signal/Noise, Simple Experimental Design, Large, Long-time Experiments, Easy to Analyze. Problems: Two-dimensional Foams Have Different Properties From Three-dimensional Foams.

•Optical Tomography: Moderately Fast, Good Signal/Noise, Long-time Experiments, Easy to Analyze. Problems: Only Very Dry Foams, Small Total Number of Bubbles.

•Optical Scattering Techniques: Fast, Good Signal/Noise, Long-time Experiments, Very large Samples. Problems: No Information on Individual Bubles.

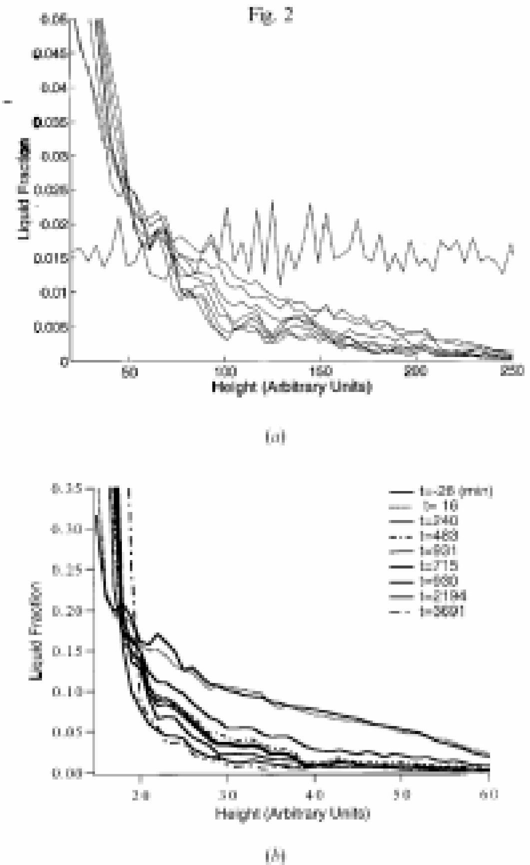
•MRI: Sample does not move, Simple Experimental Design, Long-time Experiments. Problems: Very Slow, Limited Total Number of Voxels, Very Poor Signal/Noise.

•Standard X-ray Tomography: Sample does not move. Easily Available Apparatus. Problems: Slow, Optical Density Low, Poor spatial resolution at high speeds

•Synchrotron-based Tomography: Faster, High Resolution. Problems: Slow, Sample Must Rotate, Small Sample Volume, Poor Signal/Noise

•Ratio, Movement Induced Artifacts.

Drainage



Liquid profiles for free drainage as a function of time: (*a*) Potts model simulation; (*b*) MRI experiment data.

MRI Results

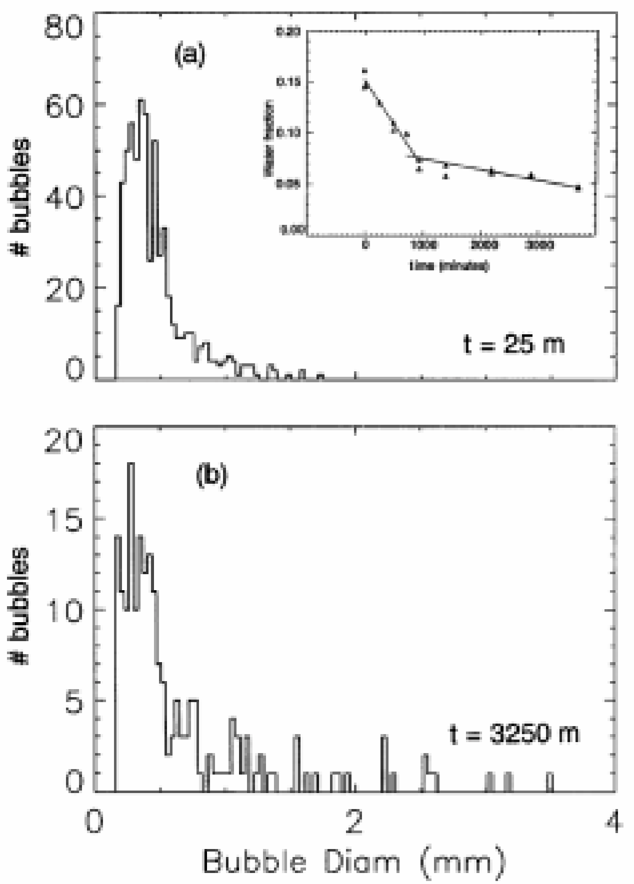


FIG. 2. Bubble size distribution at succesive times of same cross section as Fig. 1 (a) at $t = 25$ min, (b) at $t = 3250$ min. Note the extended tail of large bubbles in (b). Inset: liquid fraction in foam slice vs time. Linear fits to drainage rates are superposed.

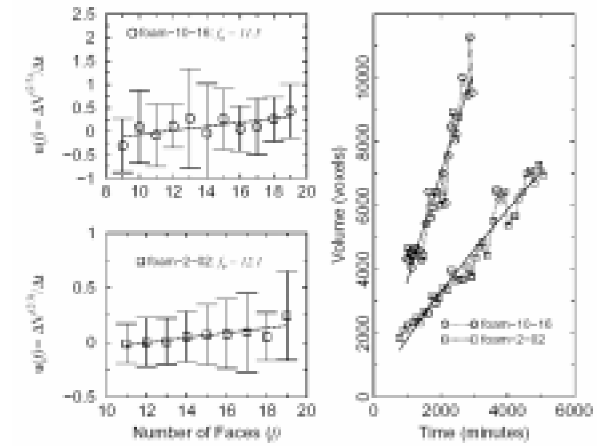


FIG. 5. Left: Time averaged volume rate of change as a function of number of faces, f, for two foams. Right: $\langle V(t)\rangle$ for the same two foams. The different slopes are proportional to the diffusion coefficients in the foams.

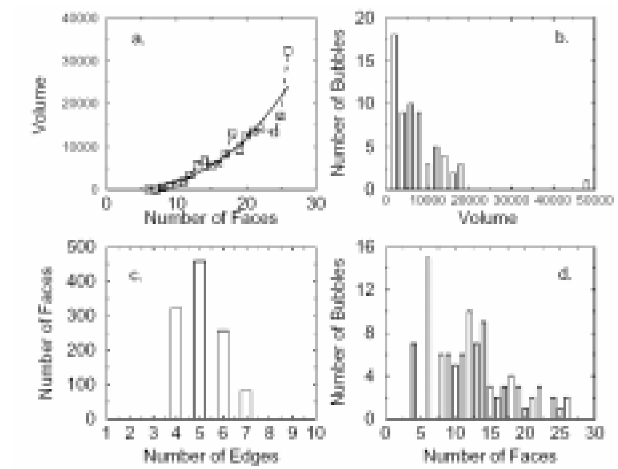
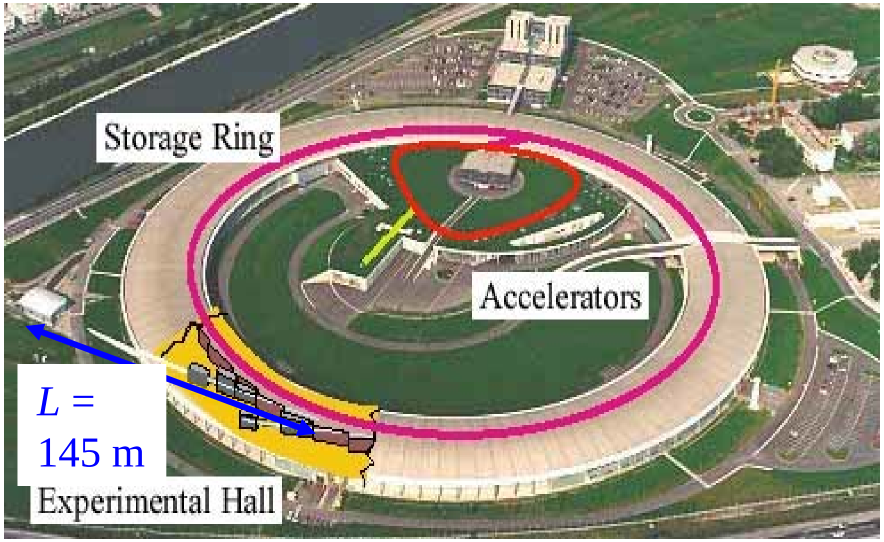
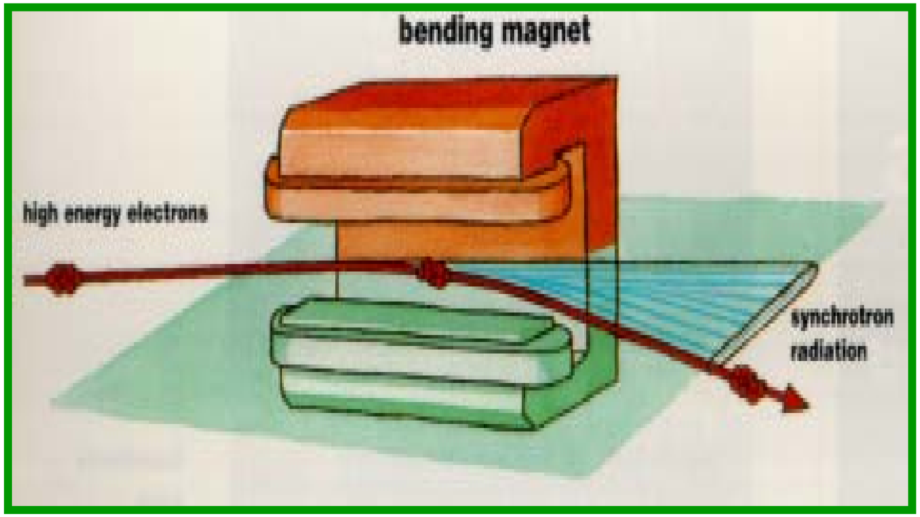
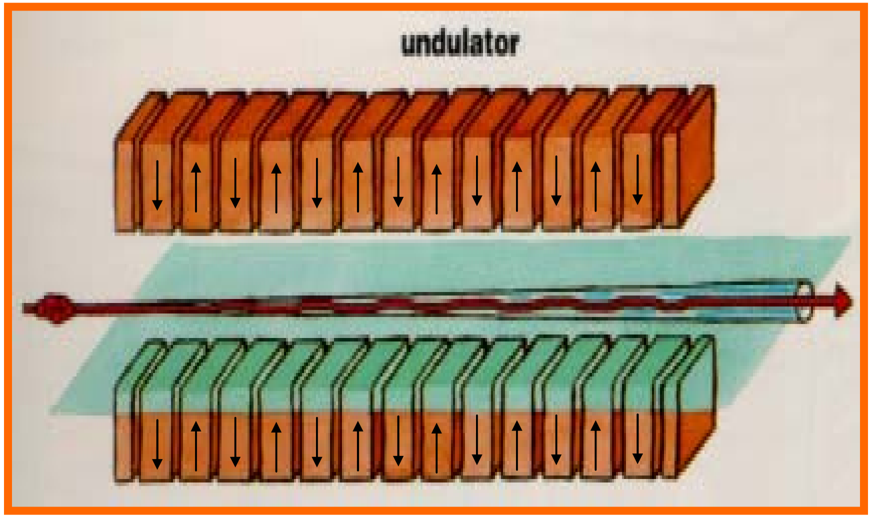


FIG. 2. Detailed structural information from a single data run for a dry foam ($\Phi < 3\%$) at t = 36 hrs. (a) $\langle V_f \rangle$ vs. f. The exponent $\alpha = 2.7$. Distributions of: (b) Volumes. (c) Edges. (d) Faces. Distributions (b) and (d) are wider than at early times, when the foam is much more ordered.

ESRF Synchrotron Radiation







Synchrotron Radiation

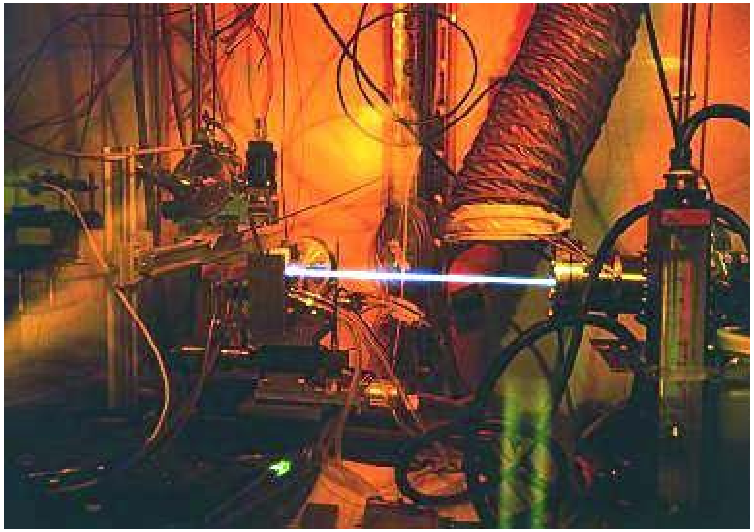
- High photon flux

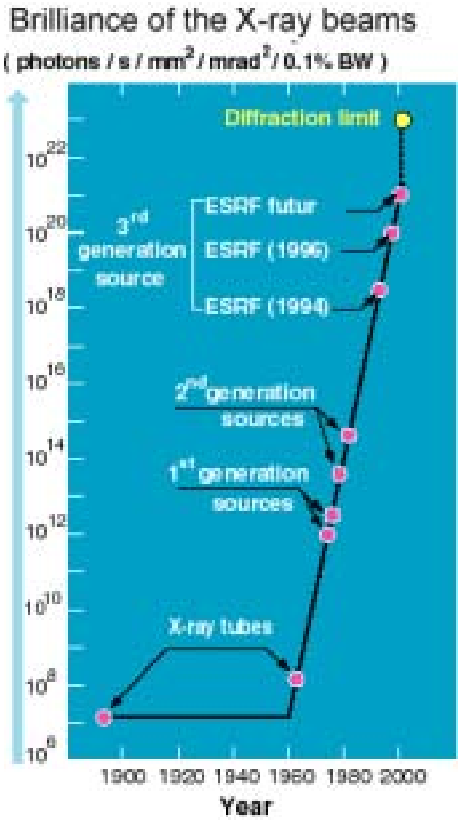
  Possible to work monochromatic
- Parallel beam
- Large or tunabale energy spectrum

- Coherent beam

  ESRF, ID19 Beamline:

  $$\left.\begin{array}{l} L = 145\ \mathrm{m} \\ s \approx 25\ \mu\mathrm{m} \end{array}\right\} \quad l_{coh} = \lambda / 2\alpha \approx 250\ \mu\mathrm{m}$$

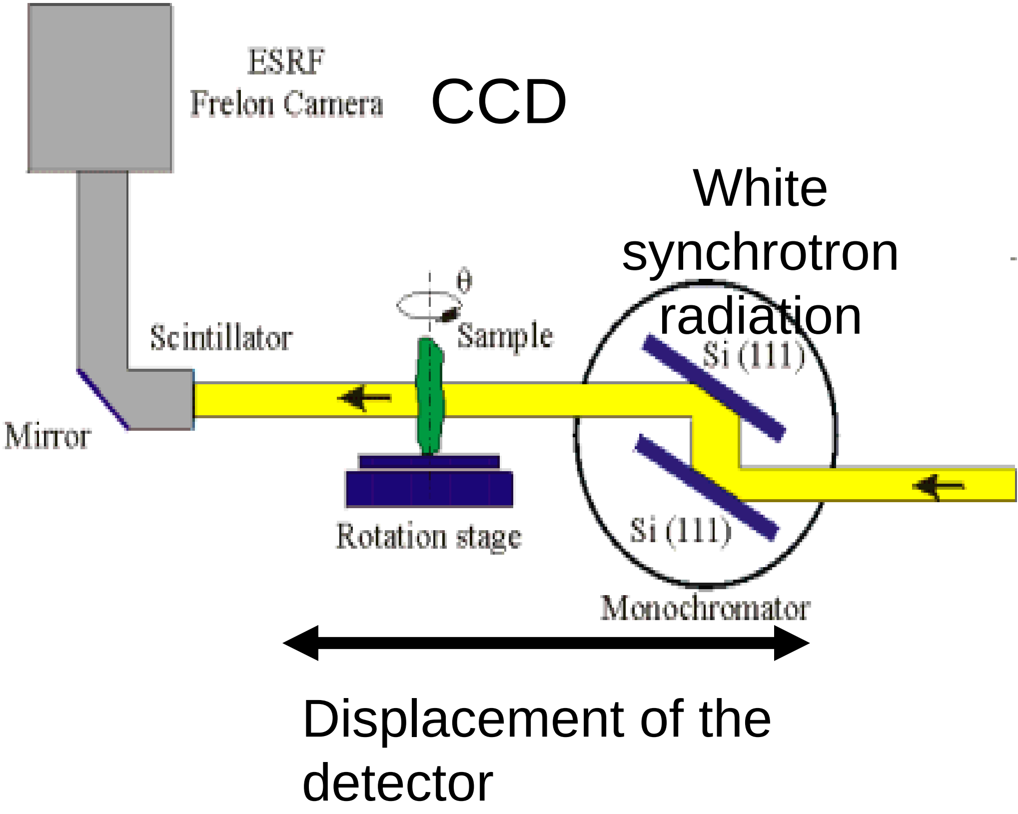




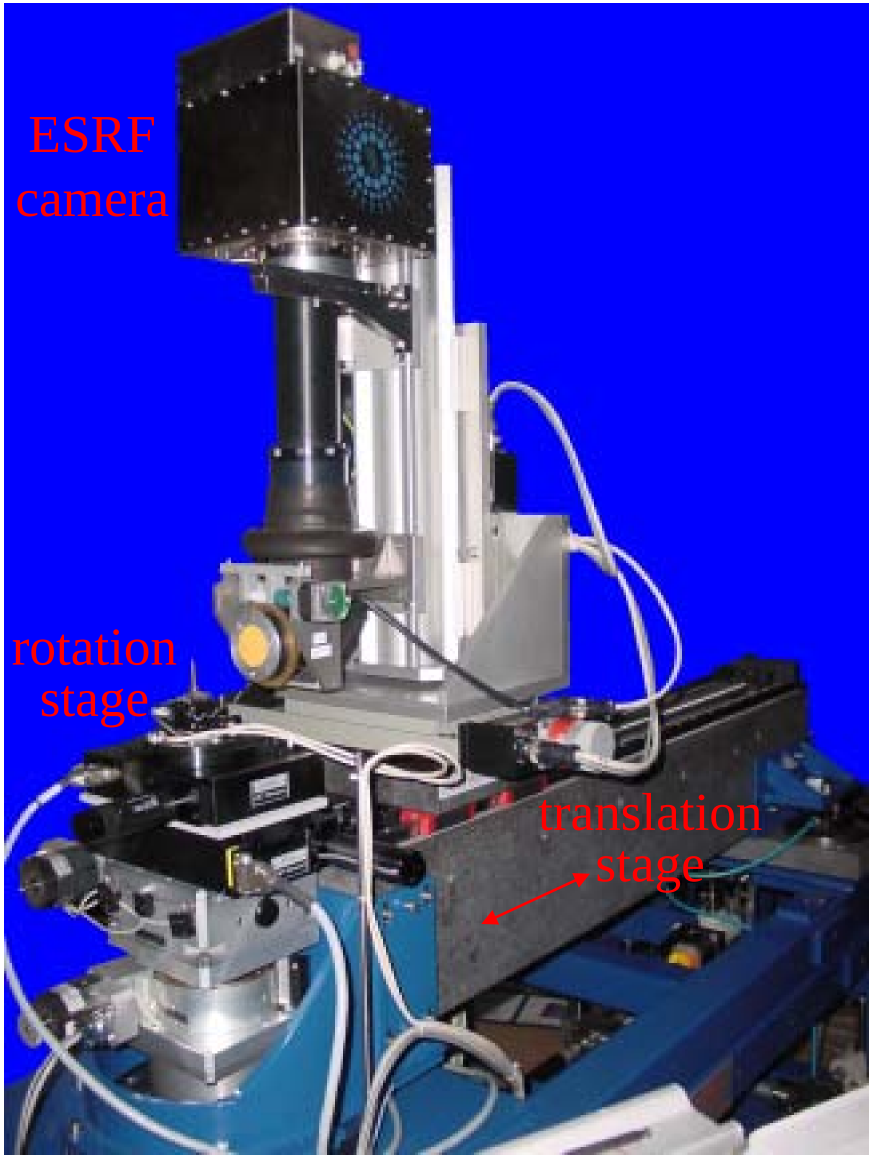
ESRF

ID 19 Beamline Parallel beam acquisition set-up

- 150 m beam
- ➔ Plane wave
- ➔ Large section beam



Microtomography setup



Implemented on ID19 / ESRF

Dedicated μ–tomograph

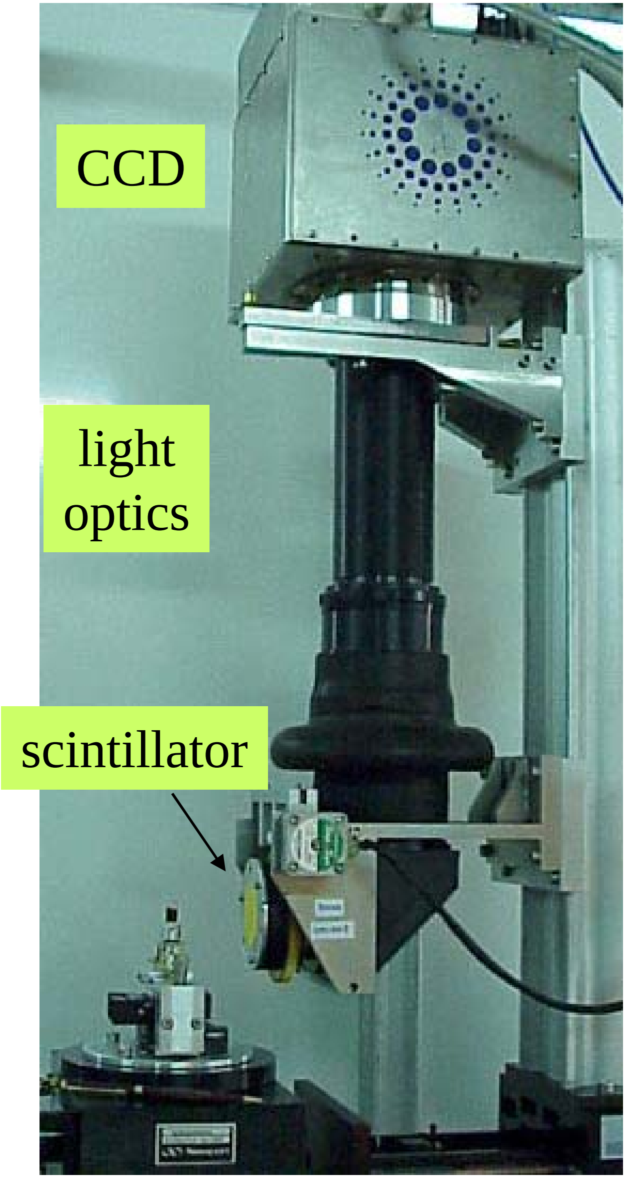
(P. Bernard)

Detector:

X-ray / visible light conversion
light optics
FRELON CCD camera
(2k*2k and 1k*1k)
Fast REad-out LOw Noise
14-bits *and* 60 ms read-out
(J.C. Labiche)

down to 0.5 μm spatial resolution
(A. Koch)

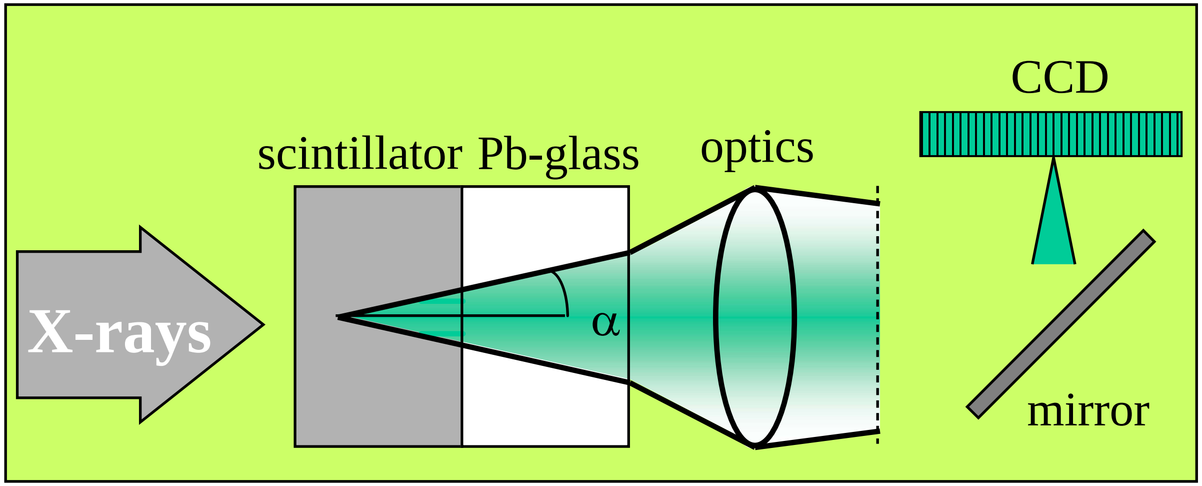
Experimental Setup



Effective pixelsize ranging from 0.3 µm to 40 µm

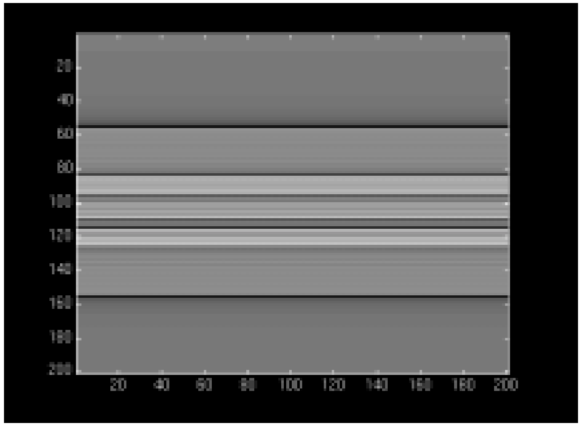
Resolutions down to 5 µm
Thin GADOX converter screens

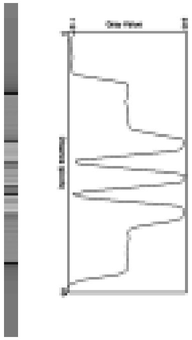
Resolutions better than 5 µm
Transparant YAG:Ce or LAG:Eu crystals

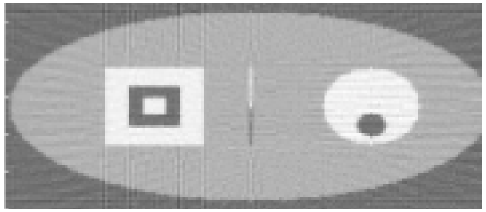


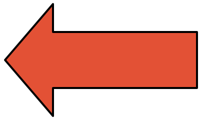
(A. Koch, J. Borrel)

About tomography 1





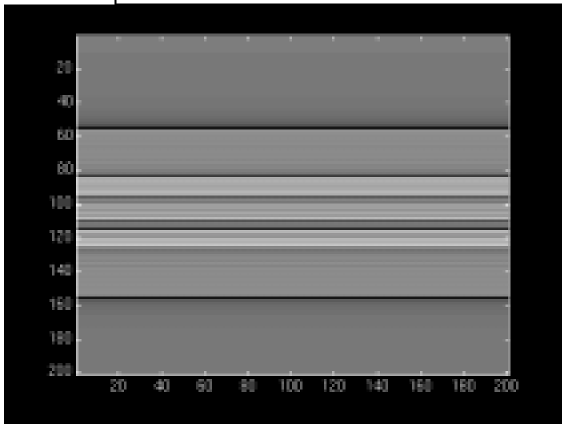




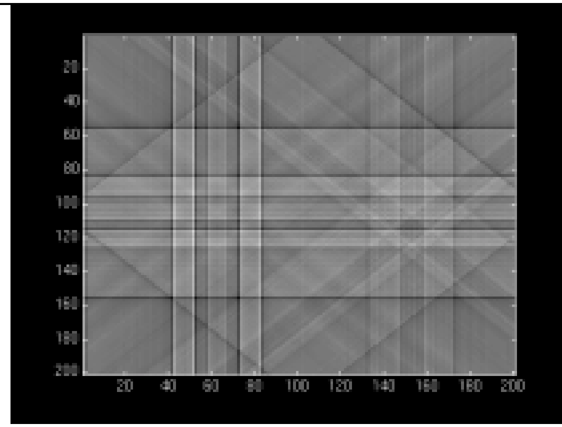
X-Ray

http://www.owlnet.rice.edu/~elec431/projects96/DSP/bpanalysis.html

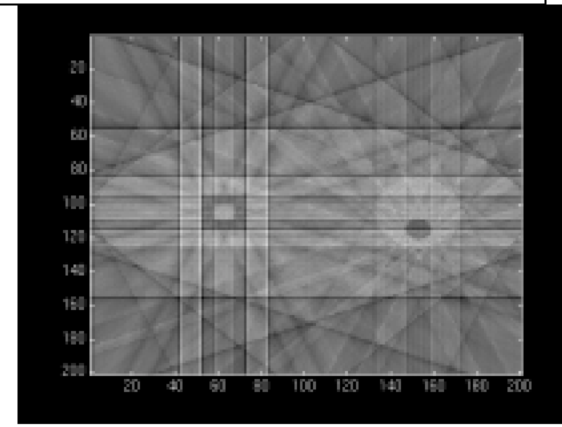
About tomography 2



1 angle

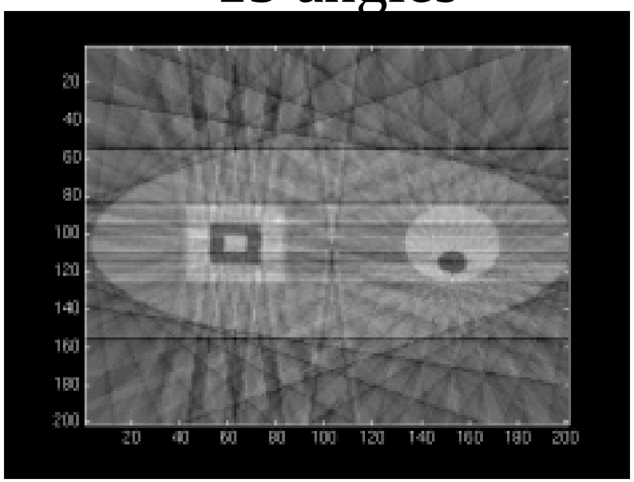


4 angles

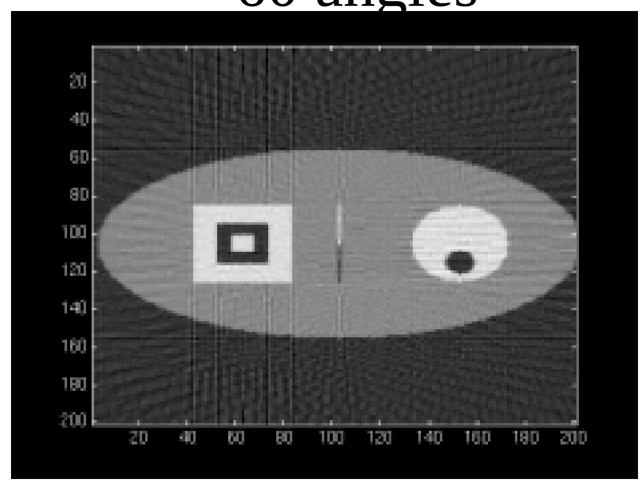


8 angles

15 angles



60 angles

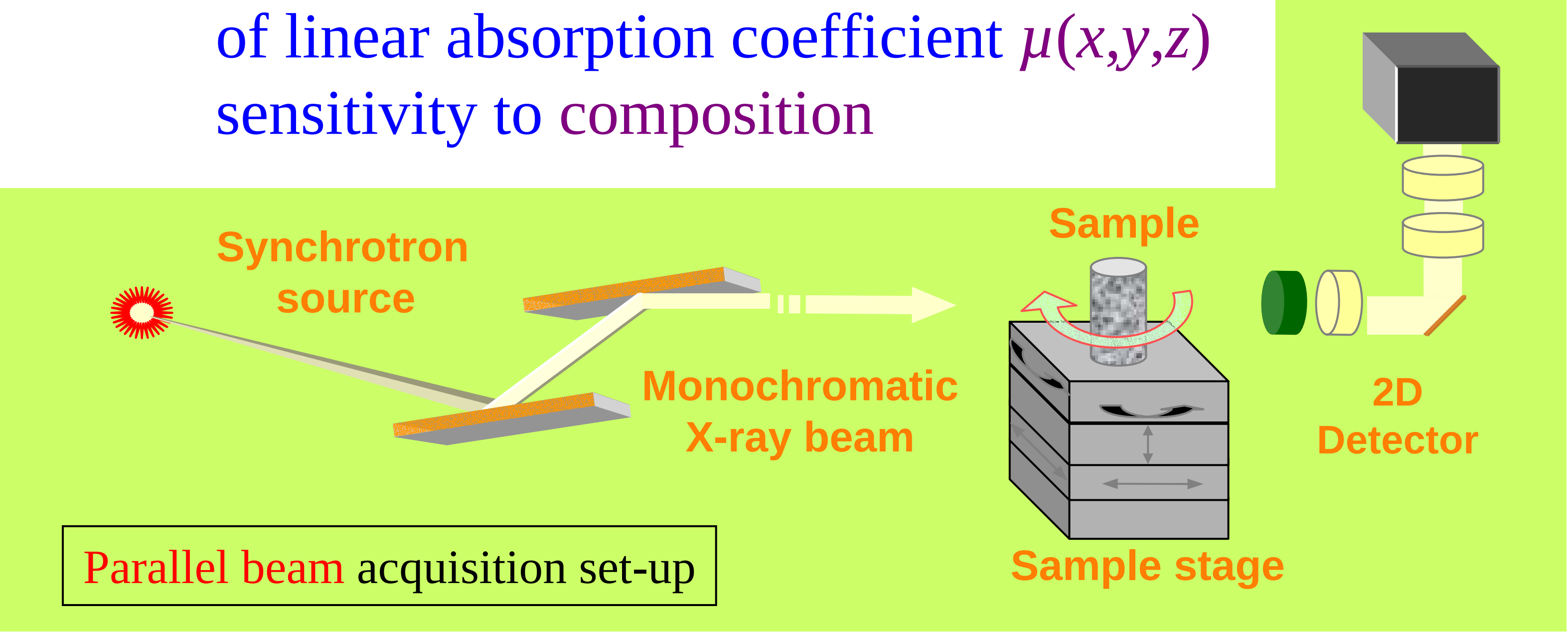


http://www.owlnet.rice.edu/~elec431/projects96/DSP/bpanalysis.html

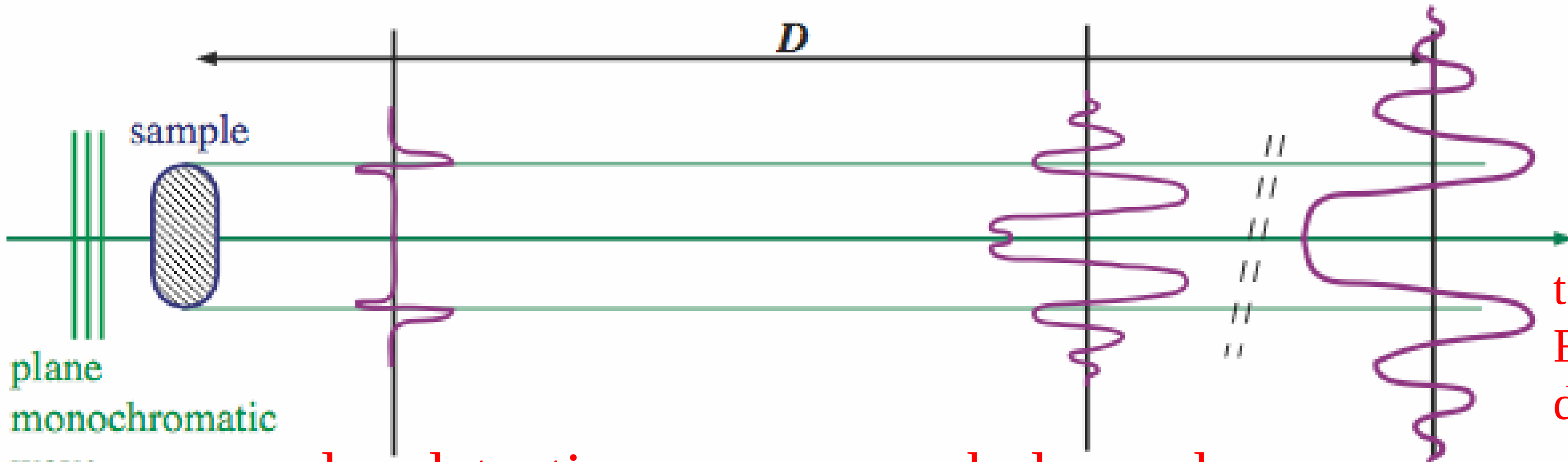
Absorption Tomography

High flux, monochromatic beam yields:

- High spatial resolution
  - approx. 1 µm
  - 1024^3 volume in 15 minutes
- High signal to noise ratio
- Quantitative reconstruction
  - of linear absorption coefficient $\mu(x,y,z)$
  - sensitivity to composition

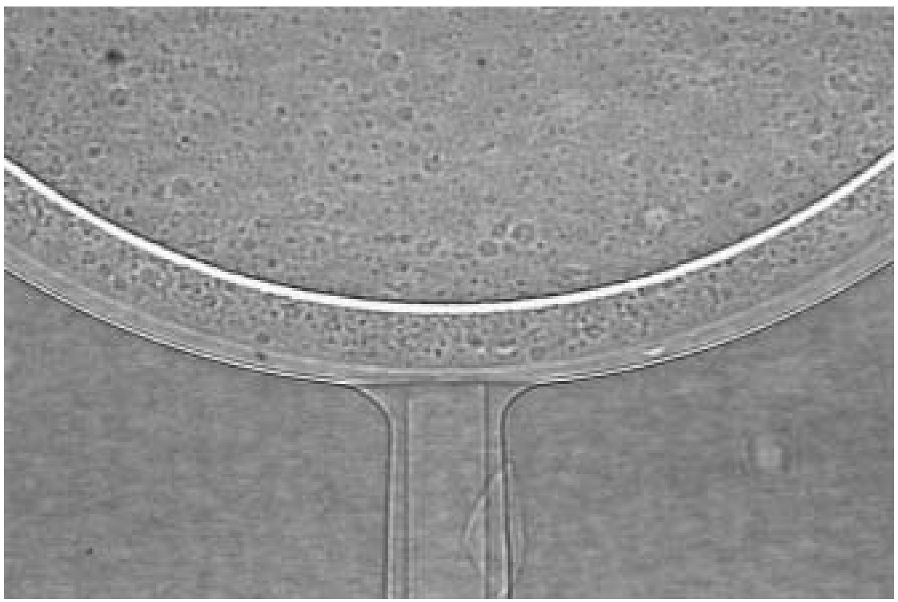


Parallel beam acquisition set-up



towards
Fraunhofer
diffraction

edge detection versus holography (Fresnel diffraction)



D = 15 cm

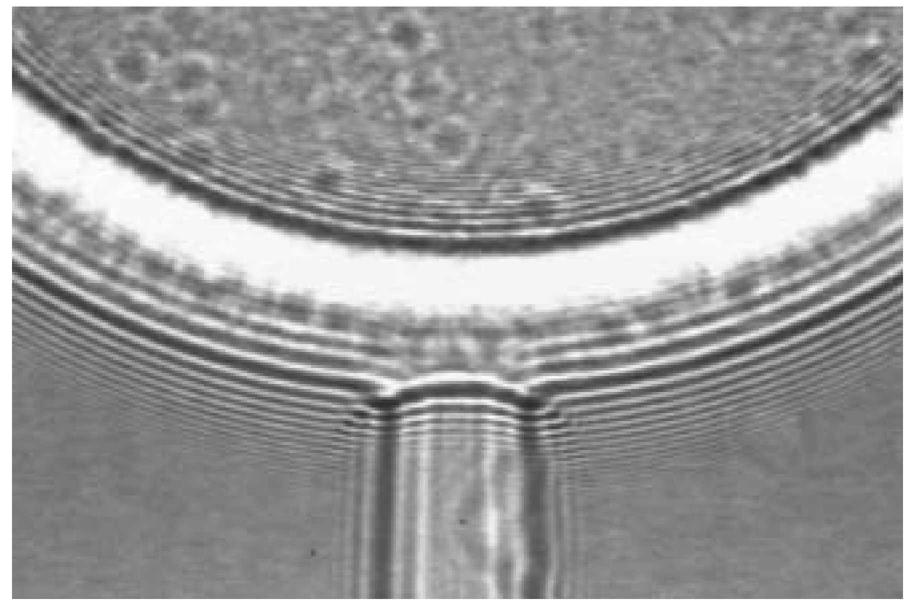
each edge imaged independently

no access to phase, only to border

$$\boxed{\sqrt{\lambda D} << a}$$

λ = 0.7 Å

50 µm



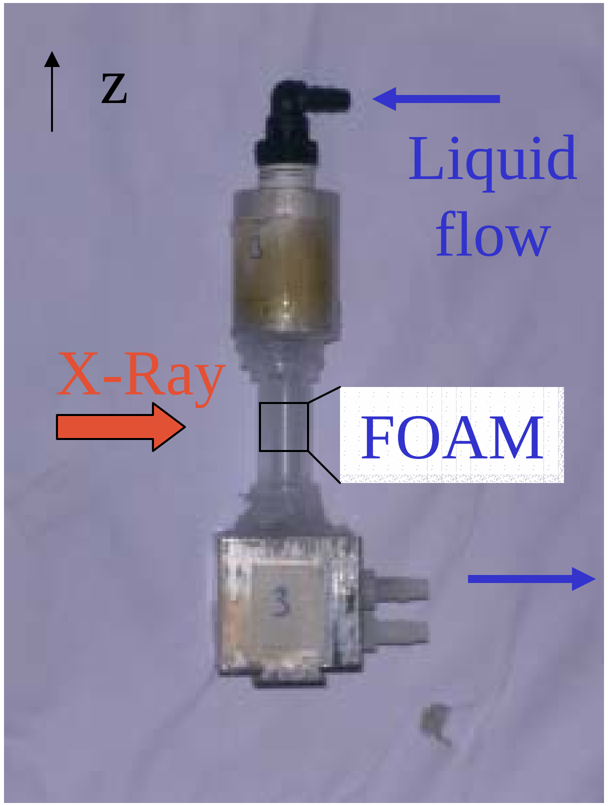
D = 310 cm

defocused *image*

access to phase, if recorded at ≠ D’s

$$\boxed{\sqrt{\lambda D} \approx a}$$

Foam cell



- Z-axis rotation
- 1000 images 1024*1024
- Scanned volume

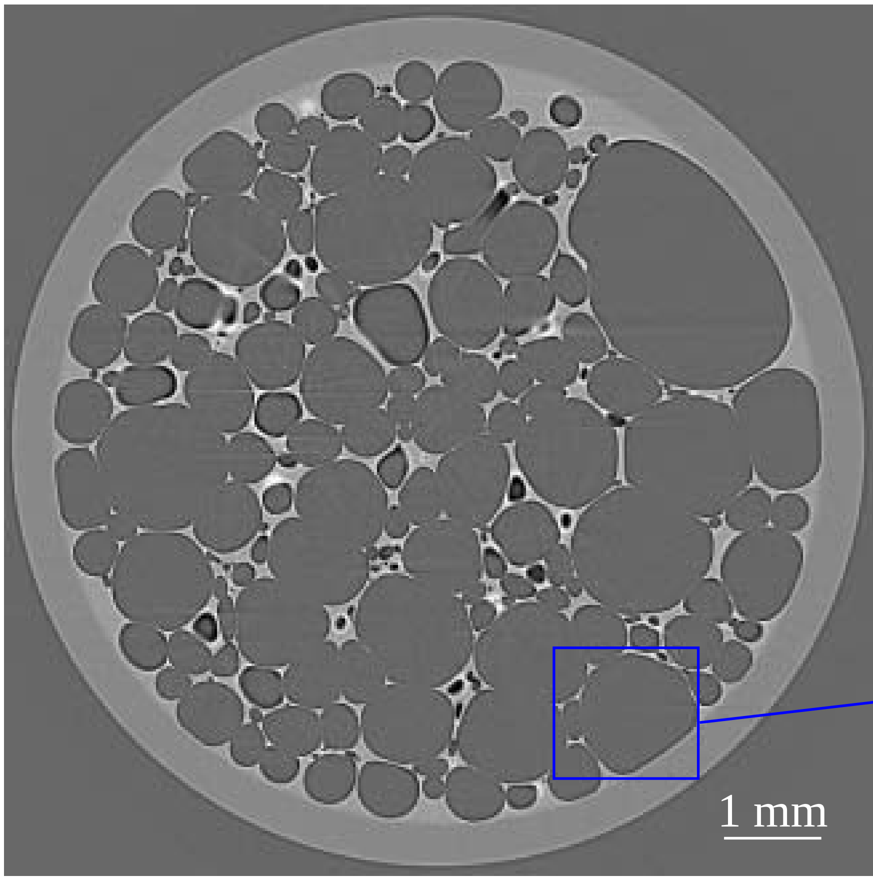
  ~ 1 cm^3

Robust foam :
Water:100 mL
SDS: 0.1 g
Dodecanol: 0.003 g
Gelatine: 1 g

Phase Contrast: Liquid Foams

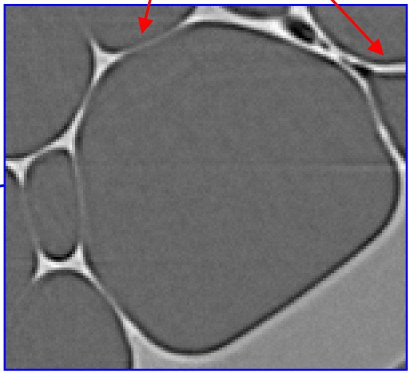
Scientific Case:

Evolution (coarsening, drainage) of liquid foams in 3D



Phase enhancement to visualise liquid films separating bubbles: Film thickness << voxel size

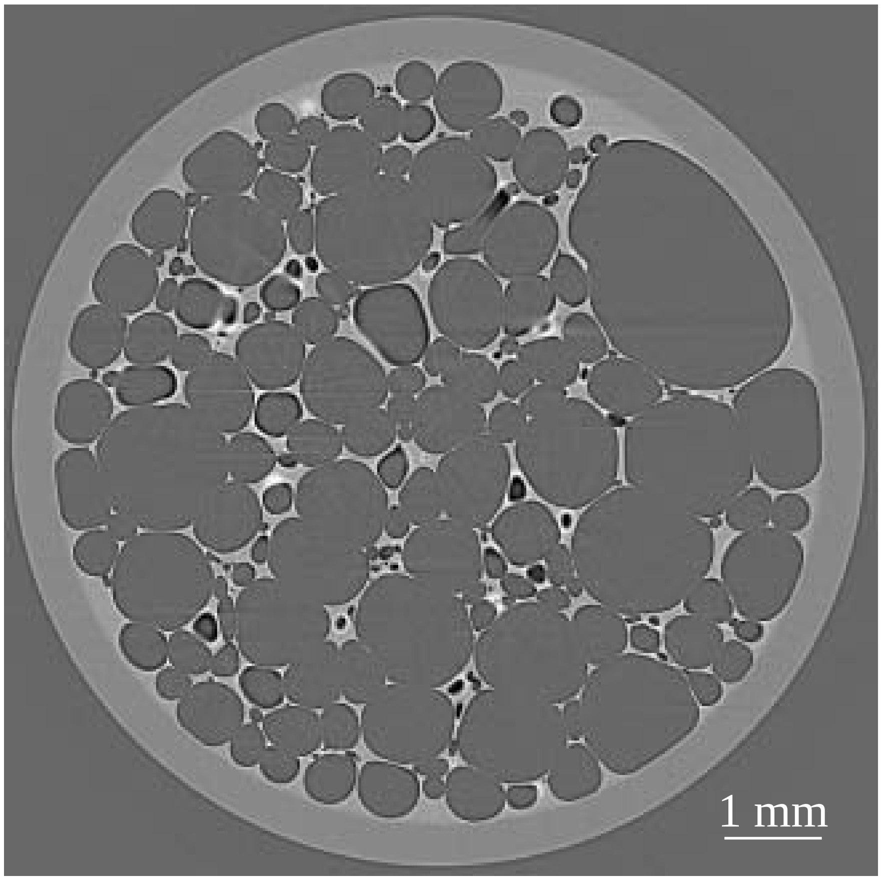
thin films



E = 15 keV, Sample-detector distance: 0.15 m

F. Graner (UJF), J. Glazier, P. Cloetens

Comparison to MRI Data



E = 15 keV, Sample-detector distance: 0.15 m

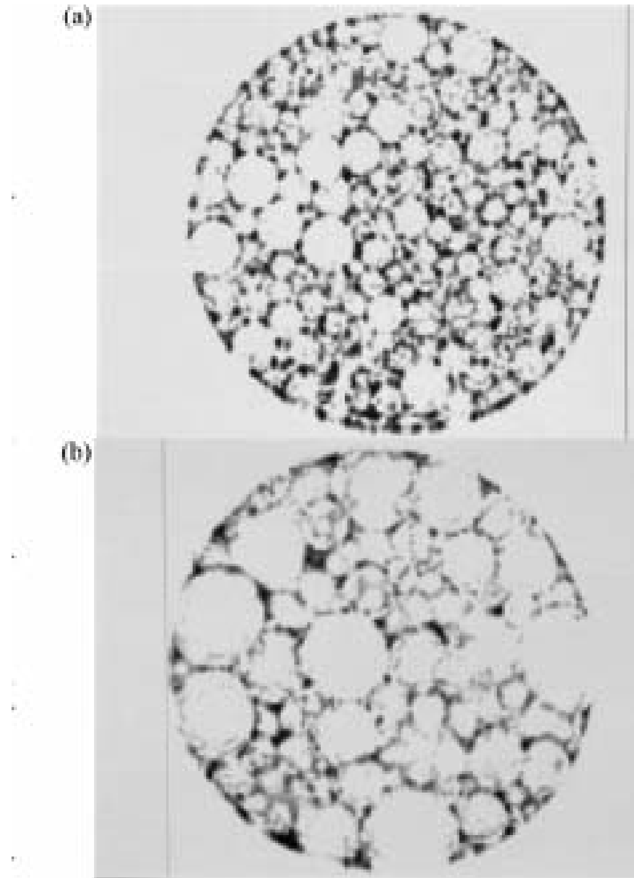


FIG. 1. (a) Horizontal foam cross section, 3 mm from bott of cell at 263 min from beginning of observations. (b) Sa cross section, 3250 min from beginning of observations. Sc is given by 1.4 cm inner diameter of sample cell.

Projection of 3D Dry Foam MRI vs Synchrotron X-Ray Tomography

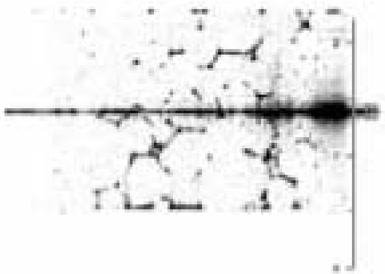


FIG. 3. Left: center slice of a reconstructed foam, showing artifacts and noise. Right: The same image after processing to remove random noise and artifacts.

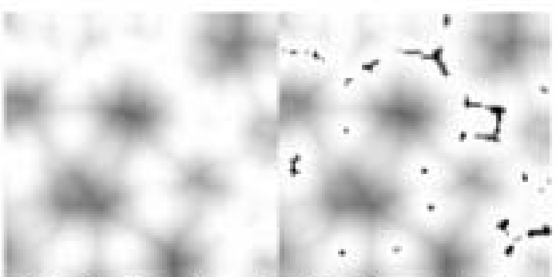


FIG. 4. Left: Slice of a three-dimensional Euclidean distance map. Right: The same map superposed on the corresponding raw image slice in a late stage foam. Darker pixels are farther from the nearest fluid edge.

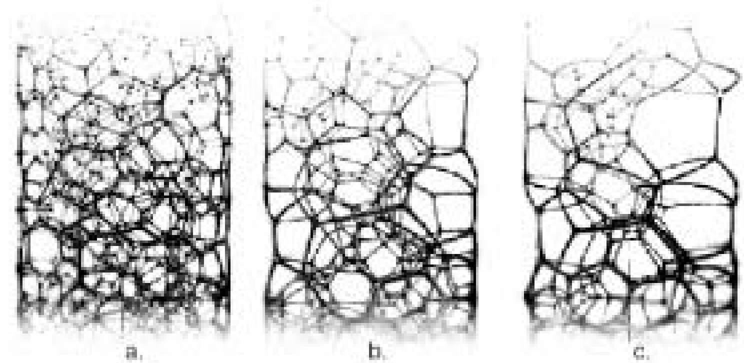
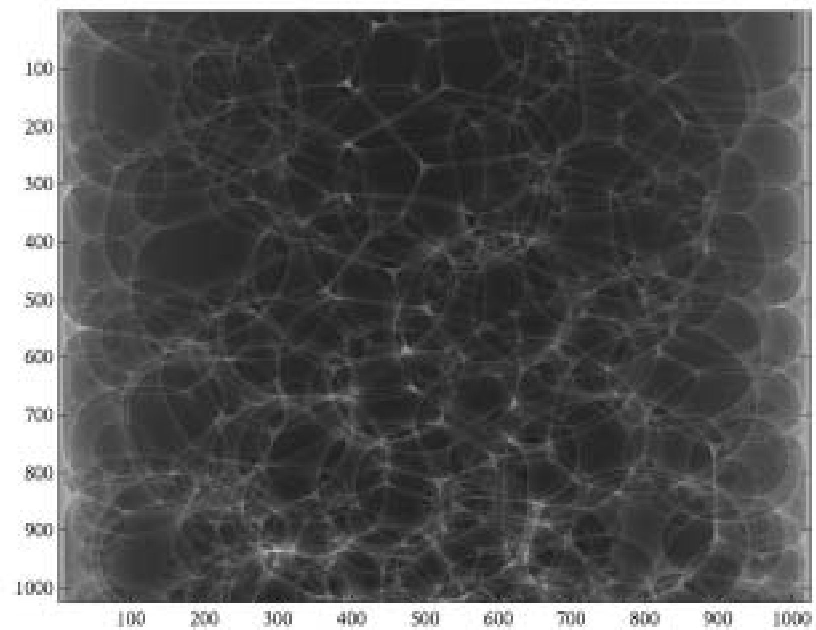


FIG. 1. Maximum intensity projections of three-dimensional MRI reconstructions of a foam at three stages of development. (a) = 24 hrs. (b) = 36 hrs. (c) = 48 hrs.



Acquisition

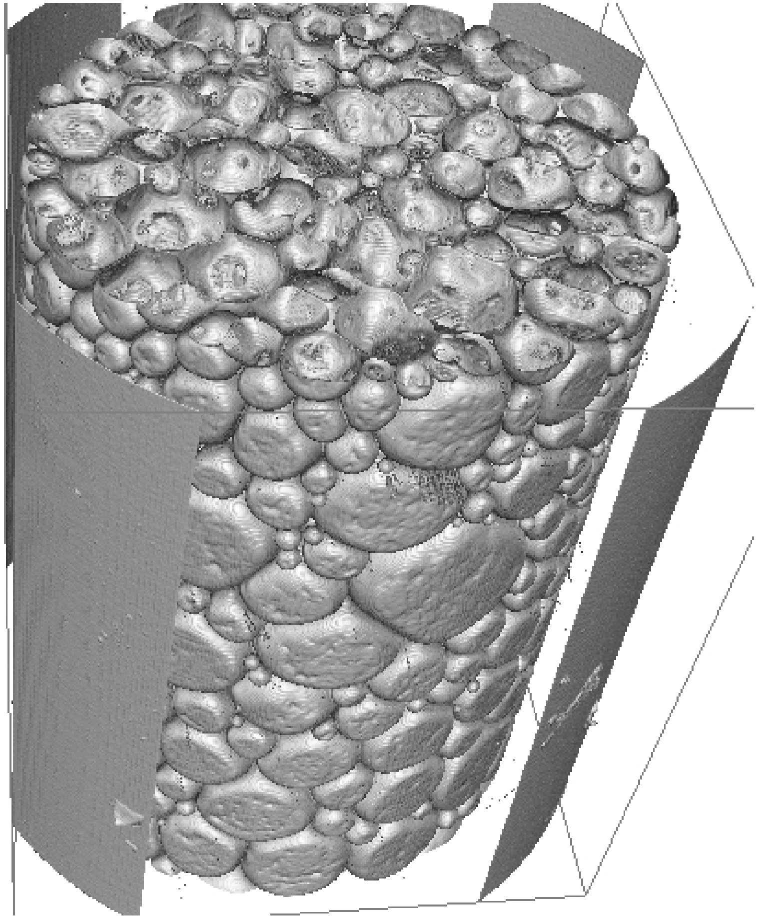
Spatial resolution:
1 voxel ~ 10*10*10 μm^3

Acquisition rate: 10 minutes

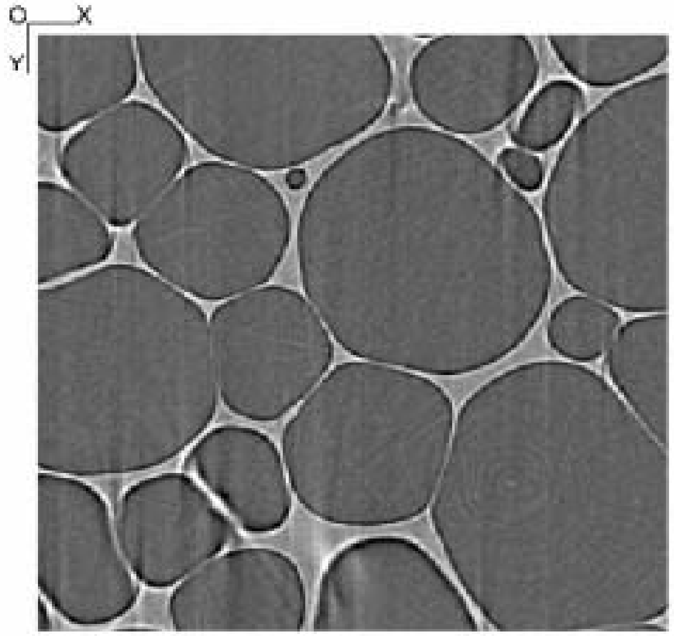
Coarsening: several hours

~100 3D-images: $(1024)^3$ grey level voxels

Play “Foam-Timescale Movie”

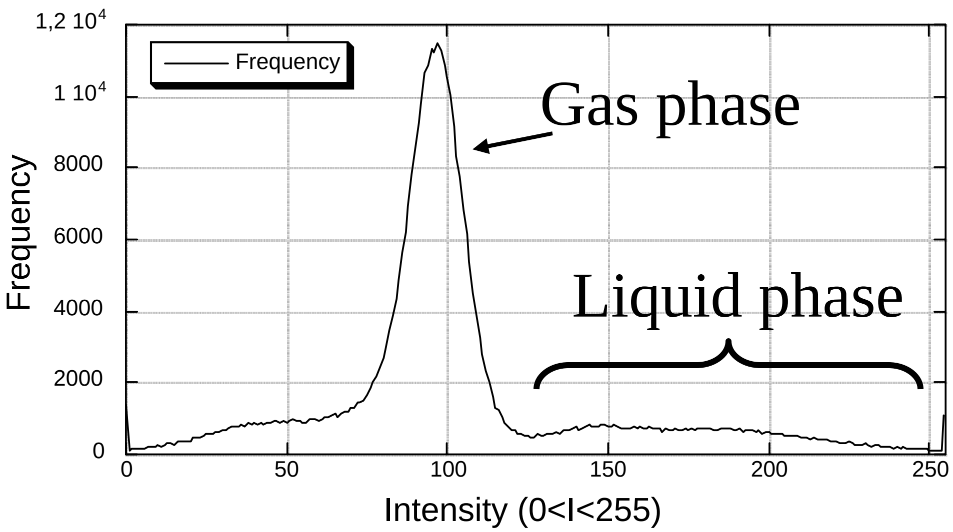


Extracting information from 3D images

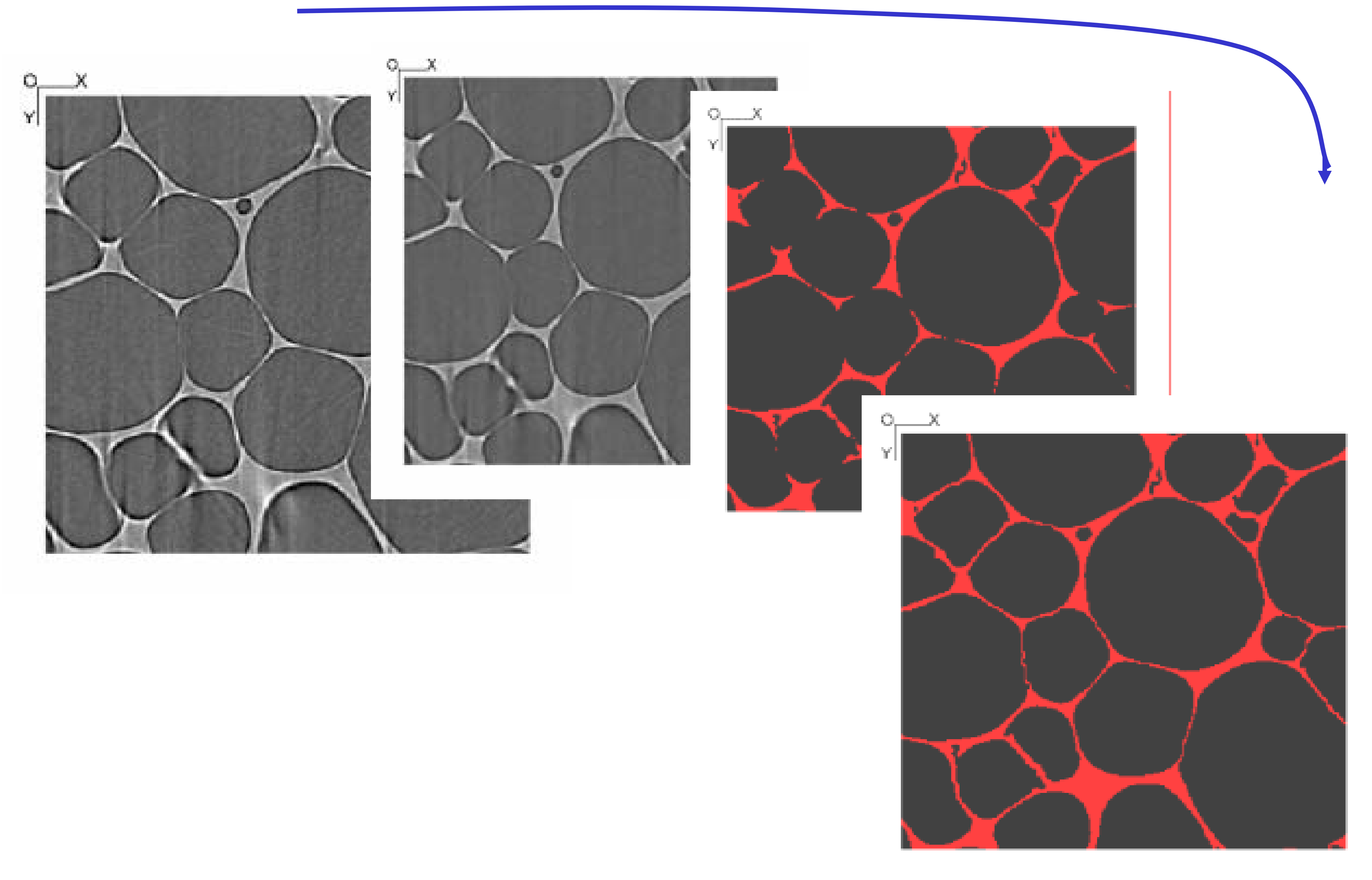


2D cut of a 3D image

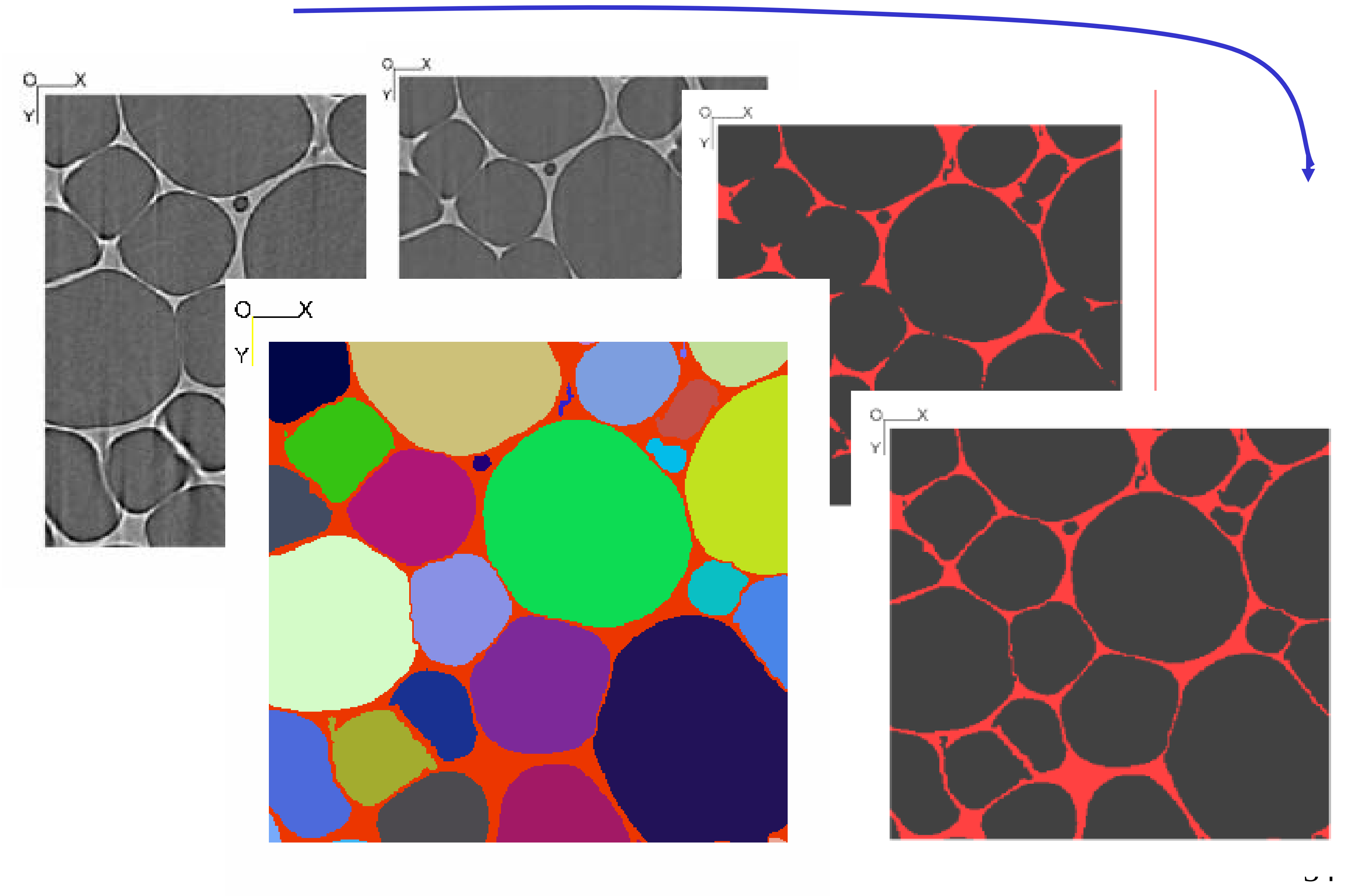
Grey level intensity distribution



Extracting informations from 3D images

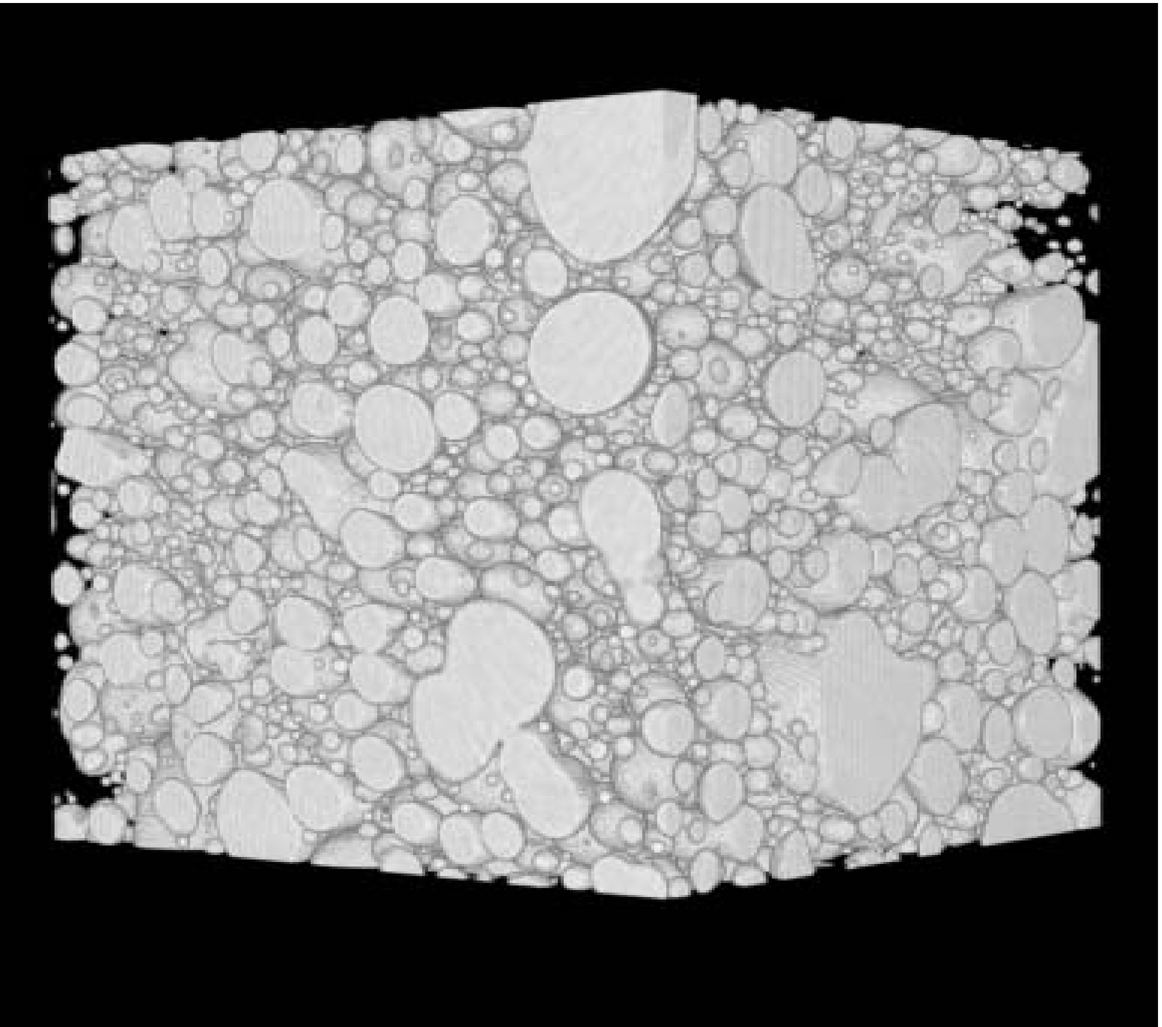


Extracting information from 3D images

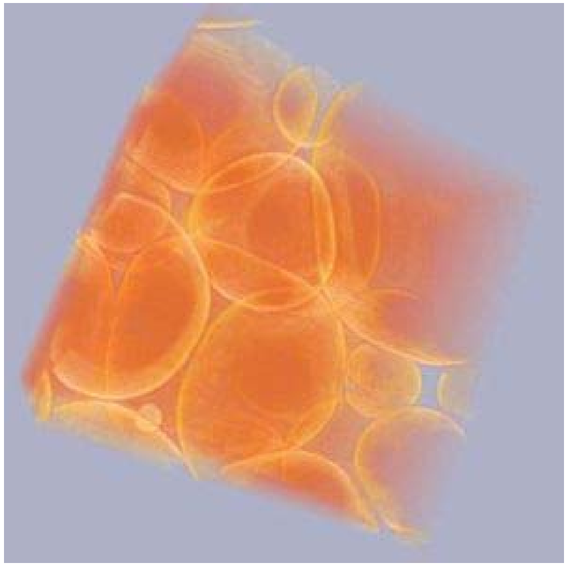


X-Ray Tomography

1 image = 1000 x 1000 pixels = résolution 10 μm
1000 images at different angles = 2.5 min
Mathematical Resonstruction = 3D information



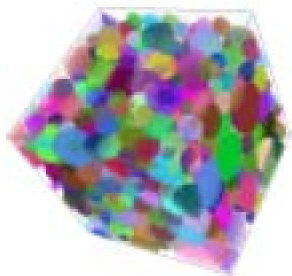
Play “Bubble.mov”



ESRF, Grenoble

Liquid Foams

Data Analysis



Segmentation
+ labelling
individual bubbles

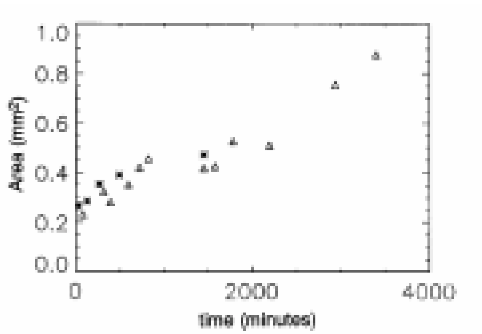
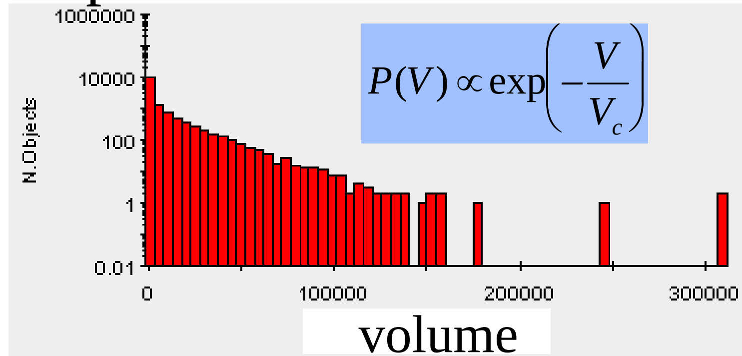


FIG. 3. Growth of average bubble area ⟨A⟩ vs time.

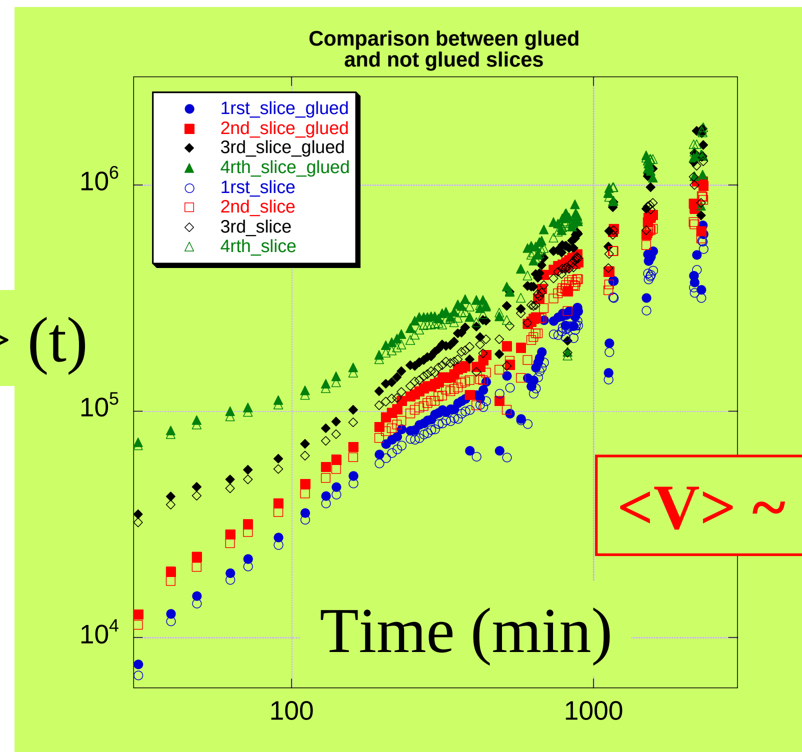
575

Exponential size distribution



$$P(V) \propto \exp\left(-\frac{V}{V_c}\right)$$

<V> (t)



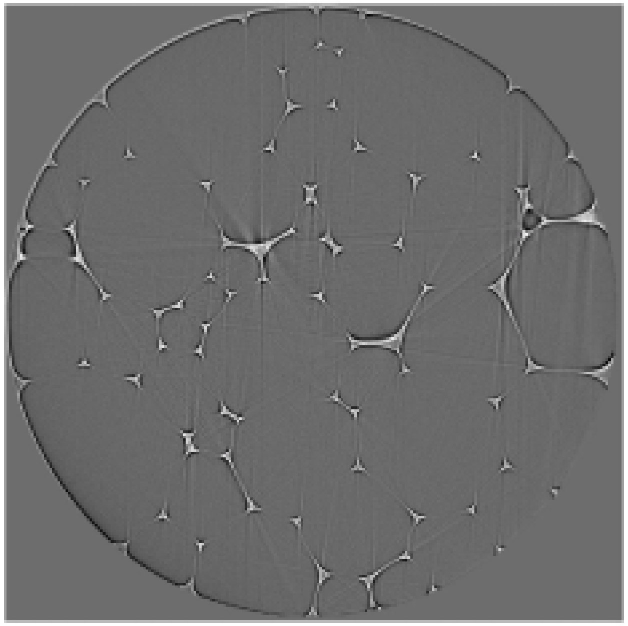
<V> ~ t

Behaves ~ as dispersed bubbles :
cf. LS mean field theory

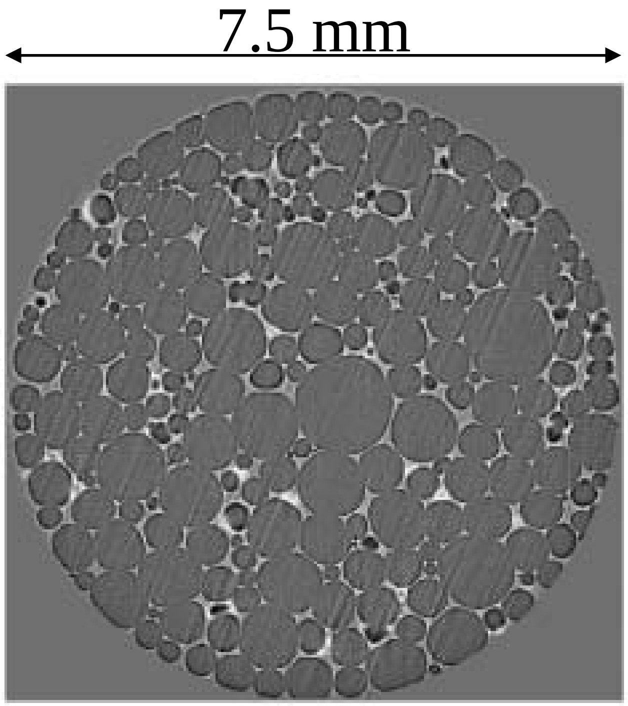
J. Lambert (Univ. Rennes)

Liquid Foams

Towards the Dry Foam limit (liquid fraction → 0)



Scan time ~ 20 sec
1024^2 ; 500 projections
40 ms / projection



Scan time ~ 6 sec
512^2 ; 300 projections
20 ms / projection

DALSA camera (12 bits): 60 images/s (1024) or 110 images/s (binned)
cf. ID15 High Energy beamline (M. Di Michiel)

R. Mokso, P. Cloetens

Key Needs

Faster Imaging

Better Signal/Noise

Smoother Sample Rotation

Larger Sample Volumes

Better Artifact Correction

Better Image Analysis Methods

Thank You!